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THE HURRICANE FAULT IN SOUTHWESTERN UTAH.

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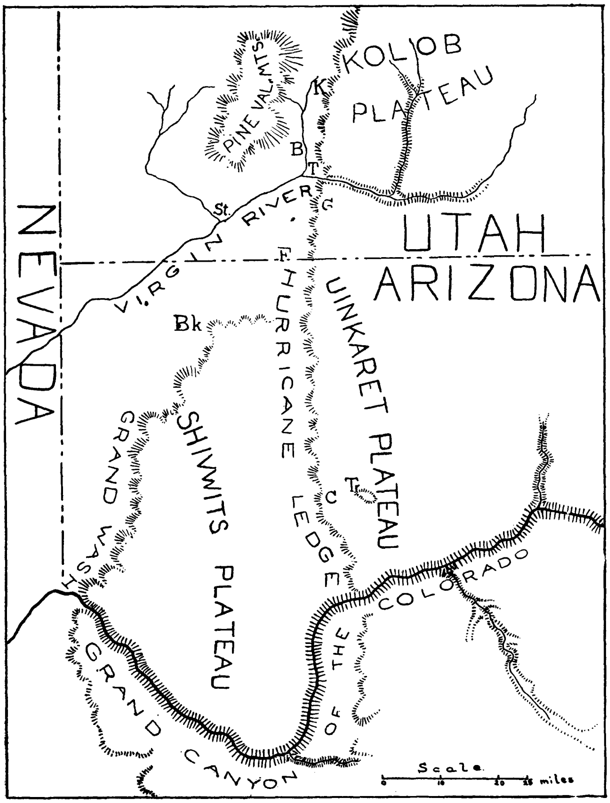
SUMMARY.

DURING the summer of 1902 the writers, under the direction of Professor William M. Davis, of Harvard University, made a study of the region around Toquerville, in the southwestern corner of Utah, on the line between the High Plateau province and the Basin Range province. Some stratigraphic work was done, and an area of about two hundred square miles was mapped. The main interest, however, centered in the relative age of the two displacements by which the plateaus of the Colorado river were elevated above the region of the Basin Ranges, and by the last of which the cutting of the Grand Canyon was inaugurated. These displacements were studied for about a hundred miles, from a point near Kanarra, twenty-five miles north of Toquerville, to the Colorado river. The older one runs almost directly south from Kanarra to the Colorado, along the Hurricane Ledge; the younger follows nearly the same course, but at the Arizona line all except a small branch turns west along a monocline and finally joins the Grand Wash fault. In this paper we shall give in outline the history of the two displacements, reserving details of evidence and references to the work of earlier observers for a more complete report which will be published later.



Sketch-Map of part of the region traversed by the Hurricane Fault.

K—Kanarra.
B—Bellevue.
T—Toquerville.
G—Gould's Ranch.
St—St. George.
F—Fort Pierce.
Bk—Black Rock Spring.
Tr—Mt. Trumbull.
C—Coal Spring.

FIG. I.

THE SEDIMENTARY ROCK SERIES.

The scarcity of known fossil horizons in the rocks of the High Plateau region led Dutton to divide that part of the conformable series between the known Carboniferous and the known Cretaceous into three formations on the basis of color and texture and a somewhat doubtful correlation with formations in neighboring provinces. To these lithological divisions he assigned the time-names "Permian," "Trias," and "Jura." Since, therefore, these names given by Dutton apply to arbitrary divisions instead of formations known to represent the three geological periods, Permian, Triassic, and Jurassic, we prefer not to adopt them, but to use only local names for those formations whose exact age is questionable, retaining the one already in use—Shinarump—and applying new names to others of the series, as shown in the following table:

Eocene Tertiary	Conglomerate pink sandstone and limestone.	
Cretaceous	Yellow sandstones and shales.	
Jurassic (of Dutton)	White sandstone	Colob.
Triassic (of Dutton)	Red sandstone	Upper Kanab.
	Red sandstone and shales	Lower Kanab.
	Conglomerate	Shinarump.
Permian (of Dutton)	Chocolate sandstone Red and white shales Red shales.	Upper Verkin.
	Gray sandstones and shales Red shales	Lower Verkin.
Carboniferous	Variegated shales and cherty limestone	Super-Aubrey.
	Gray limestone	Aubrey.

SEQUENCE OF EVENTS IN THE TOQUERVILLE DISTRICT SINCE THE EOCENE PERIOD.

From Carboniferous to Eocene time, the history of the region is one of essentially continuous deposition, during which sediments accumulated in an almost unbroken series to a thickness of more than 7,000 feet. In contrast to this long period of accumulation, the post-Eocene history is one of vast changes—of tectonic movements that preceded and accompanied the Colorado Plateau uplift, of volcanic activity, and of profound erosion

—all of which will be briefly described below. The sequence is as follows:

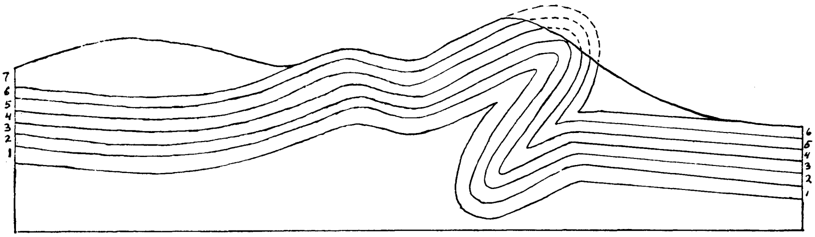
(A) Early deformation and volcanic eruptions.
(B) The first Hurricane faulting.
(C) The inter-fault or plateau cycle of erosion, ending with basalt eruptions.
(D) The latter faulting.
(E) The post-fault or canyon cycle of erosion.

DEFORMATION AND VOLCANIC ERUPTIONS.

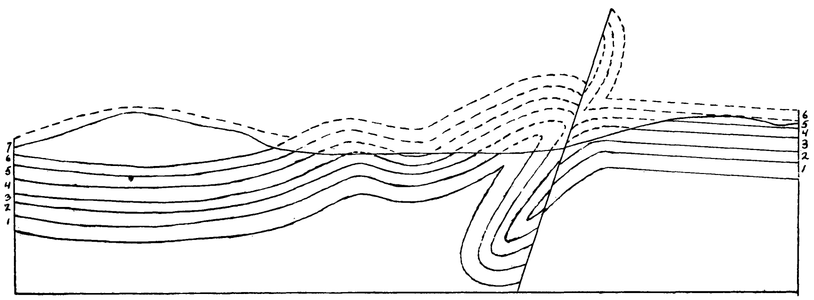
a) *Earlier folding.*—The earlier disturbance of the strata in the plateau province after their long period of quiet accumulation resulted in a number of gentle folds and flexures with slightly curved axes trending roughly north and south. In the eastern regions, according to Dutton, these were monoclinal flexures with a dip to the east by which a series of great steps was formed descending from the then relatively high Basin Range province to the lower Plateau province. In the Toquerville district the folds became intensified and took the form of well-arched anticlines and synclines. Among these more marked folds, we are chiefly concerned with the most western—a shallow syncline in which lies what now remains of the andesite mass of the Pine Valley mountains, and the most eastern—a sharp anticline that lies along the boundary between the Plateau province of relatively level strata interrupted only by the gentle monoclines, and the broken Basin Range province. South of Toquerville the sharp anticline faded out into a gentle eastward-dipping monocline, while to the north the intensity of folding increased, so that the anticline was steepened and finally at Kanarra completely overturned. The formation of these sharp folds seems to have been due to an east-and-west tangential pressure whose effects are confined to the immediate vicinity of the Pine Valley mountains.

b) *Andesite eruptions.*—The mass of the Pine Valley mountains, 3,000 to 4,000 feet thick, and twenty to thirty miles long, is composed of a heavy sheet of andesite, called by the earlier geologists a "trachyte." Wherever its base is seen, the lava lies upon a surface of Tertiary strata which seems to have suf-

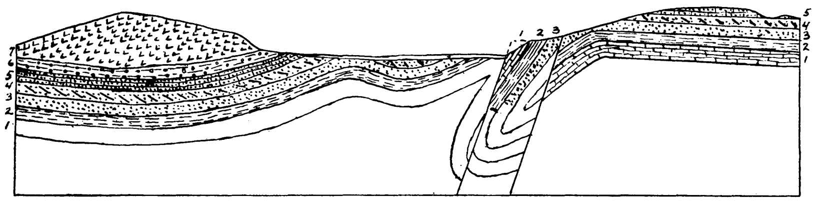
FIG. 2.



A.—Ideal section after the early folding.



B.—Restoration of section at the end of the inter-fault cycle of erosion. The dotted lines represent the sections at the beginning of the inter-fault cycle.

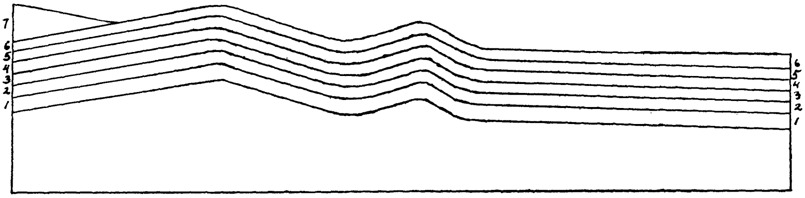


C.—Section representing present conditions.

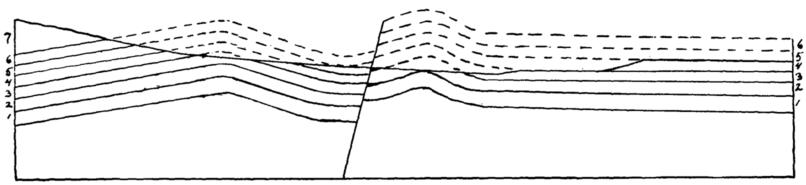
1. Aubrey limestone.
2. Verkin shales.
3. Kanab sandstone.
4. Colob sandstone.
5. Cretaceous.
6. Tertiary.
7. Andesite.
8. Basalt.
9. Alluvium.

CROSS-SECTION OF THE HURRICANE FAULT, NEAR KANARRA, LOOKING NORTH.

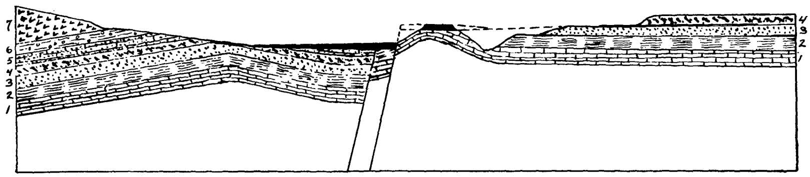
FIG. 3.



A.—Ideal section after the early folding.



B.—Restoration of section at the end of the inter-fault cycle of erosion. The dotted lines represent the sections at the beginning of the inter-fault cycle.

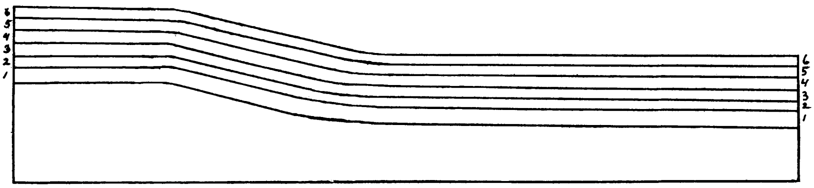


C.—Section representing present conditions.

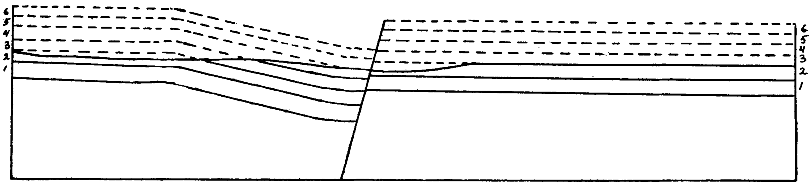
1. Aubrey limestone.
2. Verkin shales.
3. Kanab sandstone.
4. Colob sandstone.
5. Cretaceous.
6. Tertiary.
7. Andesite.
8. Basalt.
9. Alluvium.

CROSS-SECTION OF THE HURRICANE FAULT, NEAR BELLEVUE, LOOKING NORTH.

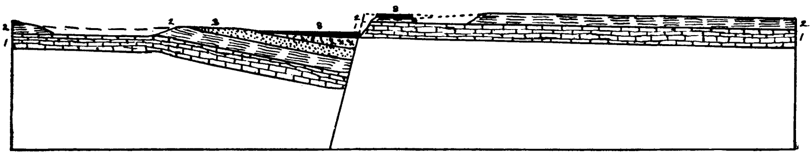
Fig. 4.



A.—Ideal section after the early folding.



B. Restoration of section at the end of the inter-fault cycle of erosion. The dotted lines represent the sections at the beginning of the inter-fault cycle.



C.—Section representing present conditious.

1. Aubrey limestone.
2. Verkin shales.
3. Kanab sandstone.
4. Colob sandstone.
5. Cretaceous.
6. Tertiary.
7. Andesite.
8. Basalt.
9. Alluvium.

Cross-Section of the Hurricane Fault, Near Gould's Ranch,
Looking North.

fered little or no erosion; hence it must have been poured out before the country had been elevated above the sea long enough to allow extensive erosion—probably long before the completion of the folding.

THE HURRICANE FAULT—THE EARLIER FAULTING.

After the folding had been completed, the tangential pressure must have been relieved and a strain of another character set up. Instead of compression there seems to have been extension, whereby numerous faults were formed which followed the lines of the old folds, but moved the strata in exactly the opposite direction, so that a new series of steps descended toward the west, and the Basin Range province stood lower, relative to the Plateau province. It is noticeable that the greatest fault took place along the line of the greatest fold, and like it increased from south to north. This Hurricane fault has been traced for fully two hundred miles. For the greater part of the hundred miles which we examined from the Colorado river to Kanarra, the displacement was a true fault, with a lift of from 2,000 to 3,000 feet; but for a short distance at Toquerville it passed into a torn flexure, accompanied by an offset of three miles to the west. North of Toquerville the fault is concealed by gravel and lava, but reappears at Kanarra, where with a much increased throw it cuts the overturned anticline already mentioned. It has long been recognized that the whole displacement of the Hurricane fault did not take place at one time, but was divided between two periods. It is thought, however, that both these periods of faulting were very recent, and there is uncertainty as to the time interval between the two periods and as to the relation which they bear to the cutting of the Colorado canyon. Evidence has been found which seems to show that the first faulting is of early date, possibly in the first part of what Dutton calls the Miocene, and has no immediate connection with the formation of the Grand Canyon. The second faulting, on the other hand, is of recent date, and accompanied the single uplift which allowed the cutting of the canyon.

THE INTER-FAULT OR PLATEAU CYCLE OF EROSION.

After the first Hurricane faulting came a long period of erosion, during which the region as a whole was reduced to a condition of moderate relief and the original topography due to folding and faulting was almost entirely effaced. Near the main drainage lines there was an approach to baseleveling, and the topographic effect of hard and soft strata was largely lost. The initial fault scarp was entirely effaced, and the line of displacement came to be marked by an escarpment on that side where hard strata overlooked soft. At the same time the south-facing cliffs on the two sides of the fault retreated northward at different rates. In the more northern district, with the head-water development of a large drainage system, a rounded sub-mountainous topography was produced. Everything indicates that the interval of erosion that followed the first faulting was very long. At the end of the period the lowlands were strewn with waste. Finally came a time of volcanic activity, when craters were formed and the old land surface was partly sheeted over with basaltic lava. It is chiefly to these basalt flows that we owe our knowledge of the two periods of faulting and of the interval between them, for they have preserved the old lowland surface. This is exposed in many places, especially where the lava sheets have been traversed by the later fault.

a) *The lava-covered Hurricane fault at Coal Spring.*— Dutton states that near the Colorado river the Hurricane fault splits into four branches, two of which must be of recent date, since they are described as cutting recent lava beds. The other two are not known to cut any lava. At Coal Spring, however, twenty-five miles north of the Colorado canyon, where no branches have been observed, an unbroken sheet of lava, showing no sign of a new fault, lies across what seems to be the main Hurricane fault, preserving a surface which is level in spite of the fact that the down-thrown side consists of soft Verkin shales and the other of hard Aubrey limestone. Since at the time of the basalt flow hard and soft strata lay side by side with an almost level surface, this part of the fault must have occurred so long before the flow that during the interval there was time for the erosion of the surface nearly to baselevel.

b) *The lava-covered surfaces on the Shivwits plateau.*—West of the Hurricane, on the Shivwits plateau, lava is seen lying on a level surface of soft Verkin shales—rocks so easily eroded that they can assume a level surface only when close to baselevel. The wide distribution of these lava-covered surfaces points to an approach to peneplaination over a considerable area in the southwest.

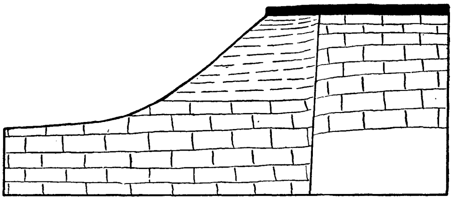


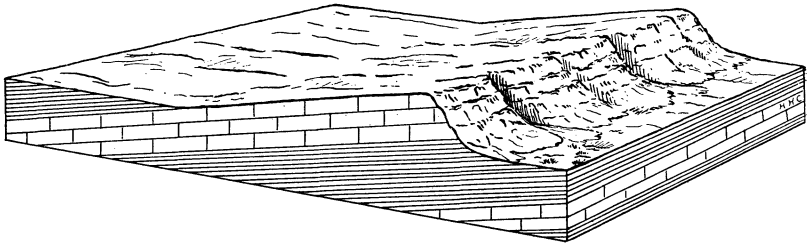
FIG. 5.—The Hurricane Fault at Coal Spring, looking north.

c) *The old fault, the old lowland surface, and the new fault.*—At several points between Fort Pierce and Kanarra, where the Hurricane fault-line is crossed by basalt flows, a displacement of two different dates is clearly shown, and it is seen that at the end of the interval between the two the relief of the region was much less than now. Where the first faulting had brought resistant strata, such as the Aubrey limestone or Upper Kanab sandstone, into contact with softer strata, such as the Verkin shales, the harder strata rose in a low escarpment, whether they lay on the heaved or thrown side of the fault. Against this the lava flowed, and thus was checked soon after crossing the line of displacement, while in other places, where the strata on the two sides of the fault were of nearly equal resistance, the lava flowed across the faults to a much greater distance. In still other cases the strata underlying the basalt are more or less tilted, but nevertheless they were reduced by erosion to a level surface that bevels the edges of the layers. Sometimes these are shales, such as those at Gould's Ranch, which under present conditions of active erosion rarely form a level surface; for they are so soft that when the overlying cap of hard strata is removed, they are at once minutely dissected into a rough bad-land topography and are soon wholly swept away, in so far as they lie above grade. In other places, as near Bellevue, five miles north of Toquerville, highly inclined layers of alternating hard and soft strata are truncated by a level lava-covered surface, although at present hard formations lying in the same attitude form marked ridges. Surfaces of all these various types have been covered by lava flows, and have been exposed to view by a recent fault or series of faults, and the renewed erosion consequent on uplift. They all indicate that between the earlier and later times of faulting there was a long period of erosion, at the end of which the region had been reduced to relatively low relief.

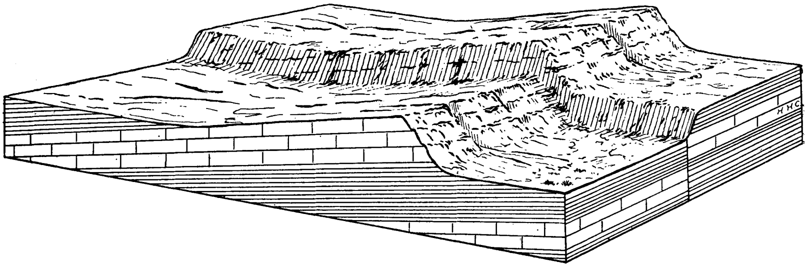
d) *Mature topography of the Colob plateau.*—Two miles north of Kanarra coarse Pleistocene gravels rest on the rather level surface formed by the dissection of the inverted strata between the old and new faults. On the gravel lies lava which seems to have come from the high plateau of Colob, east of both faults. The lava probably did not cross far west of the old fault, because it soon encountered the down-thrown Aubrey limestone which stood relatively high on account of its hardness. The recent faulting depressed the limestone area and allowed it to be covered with deep alluvium. This displacement also gave rise to a renewal of erosion by which the lava on the edge of the up-thrown block has been dissected into mesas and buttes, although back from the borders on the main mass of the maturely dissected plateau the revived activity of erosion has not as yet penetrated. The lava there lies on a surface of just the same sort as that which still characterizes the neighboring parts of the plateau which are not protected by a basalt covering. So it seems probable that the topography of the central mass of the plateau, even where it has not been protected by lava, is almost the same as that which prevailed previous to the basalt flows and the second faulting. The rounded mountainous hills, rising to a height of two or three thousand feet, the graded slopes, well-established drainage, and broad valleys, are strongly in contrast to the precipitous slopes and new aspect of the peripheral regions, and seem to represent the conditions previous to the second uplift.

e) *Differential recession of cliffs on the two sides of the old fault.*—Still another line of evidence shows that there have been two periods of faulting separated by a considerable interval of erosion. The unequal recession of outcrop cliff on the two sides of a fault is a principle that has already been discussed in connection with the plateau region. It was recognized by Powell that when a set of outcrop cliffs is cut by a transverse fault the cliffs on the up-thrown side will be subjected to more powerful weathering and erosion than those on the lower side; consequently they will retreat faster and the outcrops on the two sides will in time become discordant. Professor Davis has recently pointed out that the amount of discordance gives a measure of the length of the period of erosion that succeeded the faulting. In the plateau region the apparently level strata, which really dip slightly to the north, form steep south-facing cliffs which are gradually worn northward along their gentle dip. Since the original Hurricane fault took place the Kanab red sandstone cliffs on the eastern side have retreated over fifteen miles farther than their low-lying counterparts on the western side. Inasmuch as this distance represents, not merely the whole amount of retreat, but the excess of retreat on one side over that on the other, the time during which the process went on must have been very long.

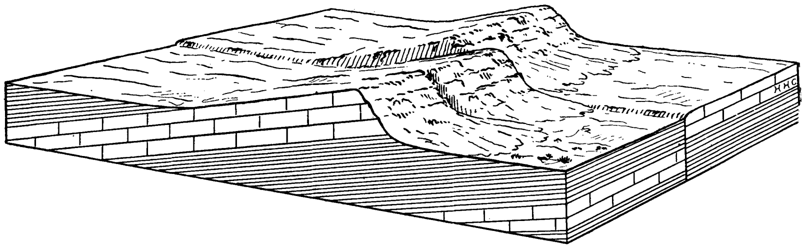
f) *General review of the topography at the end of the inter-fault cycle.*—The fragments of old surface that are preserved under the lava sheets generally belong to lowland topography, and have been examined chiefly in the subsequent valley that seems to have followed the old fault line, first on one side, now on the other, according as the strata were hard or soft. The mature mountainous hills of the old still unchanged plateau preserve the ancient form of the uplands. Between the highlands and the lowlands were long graded slopes which have now been revived into steep, rapidly receding cliffs of naked rock. All this signifies a long period of erosion — so long that the main valleys were reduced nearly to baselevel, although the more remote regions to the north were still somewhat mountainous and there was still considerable relief in the intermediate regions. At that time no Grand Canyon can have existed, although the Colorado river must of necessity have been a very important feature in the topography. Its valley must have



A.—Unfaulted block showing a continuous line of cliffs.



B.—The same block cut by a north and south fault.



C.—The same block after erosion has almost obliterated the fault scarp. The cliffs on the eastern or upthrown side of the fault have retreated much farther than those on the down-thrown side.

BLOCK DIAGRAMS ILLUSTRATING THE DIFFERENTIAL RECESSION OF CLIFFS ON THE TWO SIDES OF A FAULT.

FIG. 6.

been like those of its tributaries—a broad open depression where the river flowed on an extensive flood-plain close to baselevel. Near the end of this cycle of erosion there was extensive aggradation, forming the heavy gravel deposits of Kanarra, the Virgin river, and the Grand Wash. Then came an abundant outpouring of basalt from many craters, especially in the region that was nearest baselevel; and thus a new and very durable element was introduced into the topography.

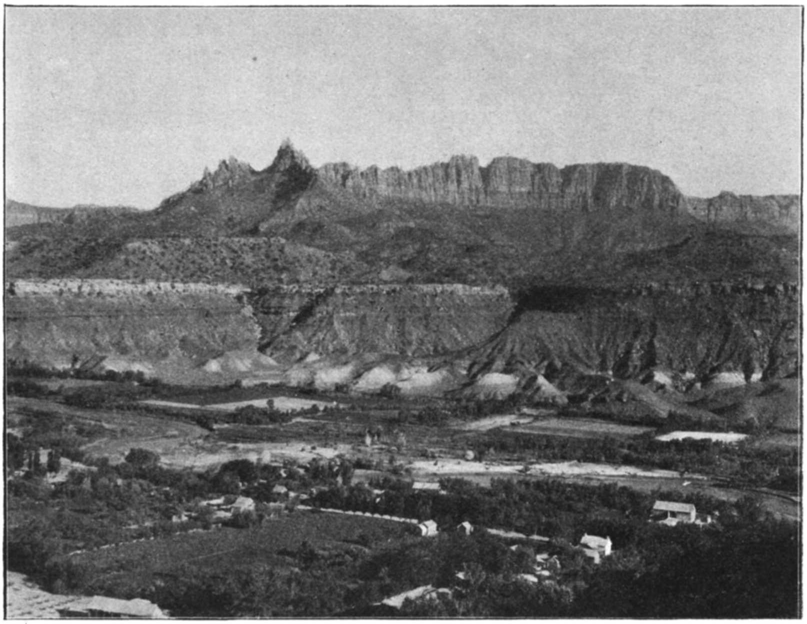


FIG. 7.—View south across the valley of the Virgin river at Rockville. The sharp cliffs of Red Kanab sandstone in the background rise 3,000 feet above the river. Below them are soft lower Kanab shales, the rapid weathering of which has undermined the Upper Kanab, causing the great landslides that are seen lying on the Shinarump platform which extends across the middle of the picture. Below the Shinarump the soft Verkin shales are minutely dissected into a bad-land topography, whose roughness and aridity contrast strongly with the irrigated fields of the Mormon village of Rockville on the flood-plain in the foreground.

THE HURRICANE FAULT—THE LATER FAULTING.

The newer displacement, like the older one, changed at Toquerville from a fault into a flexure. South of Toquerville, however, the displacement continued as a true fault to Fort Pierce, beyond which it split. One part, which followed the old fault line, seems to have greatly diminished, but, as indicated by the broken lavas that Dutton describes, was of considerable importance where it crossed the Grand Canyon. The other passed into a long gentle monocline, and, leaving the old Hurricane fault line, bent to the southwestward until at Black Rock it joined the Grand Wash fault. This, like the Hurricane, is a young displacement following the line of an old one, as is shown by the relation of lava flows to the strata preserved under them. The line of dislocation, then, which separated the uplifted Plateau province from the Basin Range province

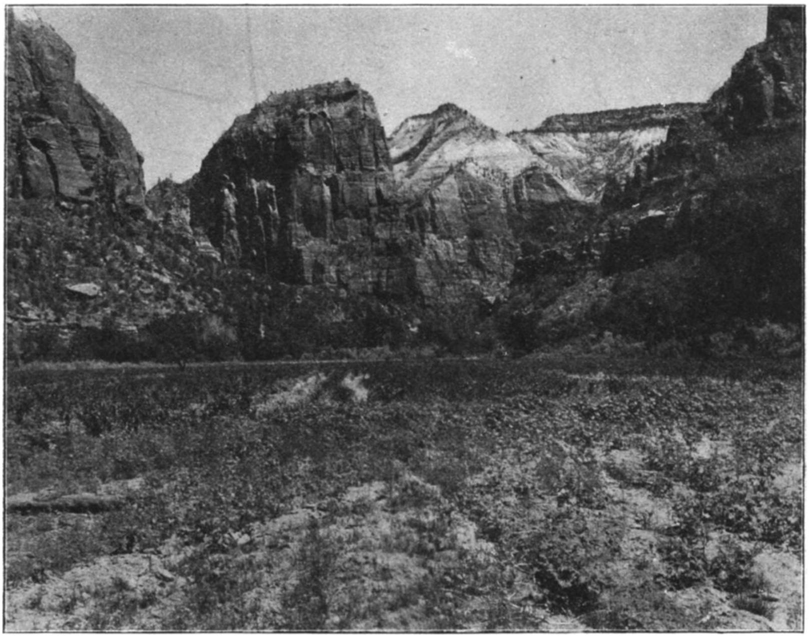


FIG. 8.—Mukuntuweap canyon, looking north. The sky-line on the right shows a portion of the mature topography of the Colob pleateau. On the left the Temples of the Virgin, of red Kanab sandstone capped by the white cross-bedded Colob formation, rise 2,500 feet. They have been carved by the erosion consequent upon the uplift which introduced the canyon cycle. The level foreground is a lake plain, formed when the stream was obstructed by landslides similar to those seen in Fig I.

reaches the Colorado river in much the greater part by the Grand Wash, and only in small part by the Hurricane. It is to this great uplift, limited on the west by the Grand Wash and Hurricane faults, that we owe the inception of the canyon cycle of erosion and the cutting of the Grand Canyon of the Colorado.

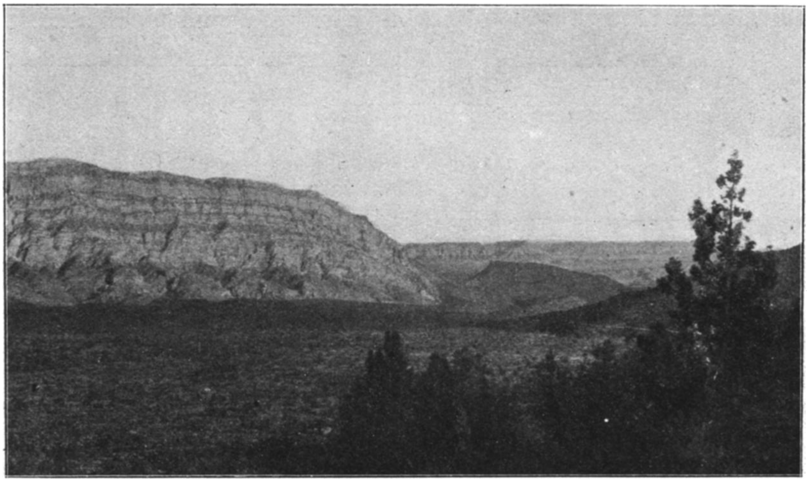


FIG. 9.—The Hurricane escarpment just north of Toquerville, as seen from the northwest. The Aubrey escarpment, 2,000 feet high on the left, diminishes as it passes into the torn flexure, which is shown in Toquer hill, the black lava-covered hill in the middle distance. Beyond this are the Shinarump-capped mesas of Verkin shales that lie east of Gould's ranch.

THE POST-FAULT OR CANYON CYCLE OF EROSION.

During and since the later uplift there has been a cutting of canyons in the hard strata, and a general stripping of unprotected soft strata. In the Plateau region erosion has gone just far enough to emphasize very successfully the topographic value of hard and soft strata. Thus, along the fifty miles of the Hurricane south of where most of the new displacement turned westward, the rapid wearing away of weak Verkin shales on the western side of the old fault line has left the hard Aubrey limestone on the eastern side as an erosion escarpment so strong that Dutton took the whole of it for an actual fault scarp of recent date. At Coal Spring, where the basalt flowed west across the old fault line onto the Verkin, the weak shales were locally protected, so that the modern cliff front at this point is west of the old Hurricane fault line. Of this 1,800-foot escarpment all but a few hundred feet is the product of erosion on the line of the old fault during the canyon cycle. There could be no better illustration of the progress of erosion since the later faulting than this, which shows that the existing cliff has been shaped almost wholly by erosion, working under the conditions imposed by the old fault, the erosion interval, the basalt flows, and the recent uplift.

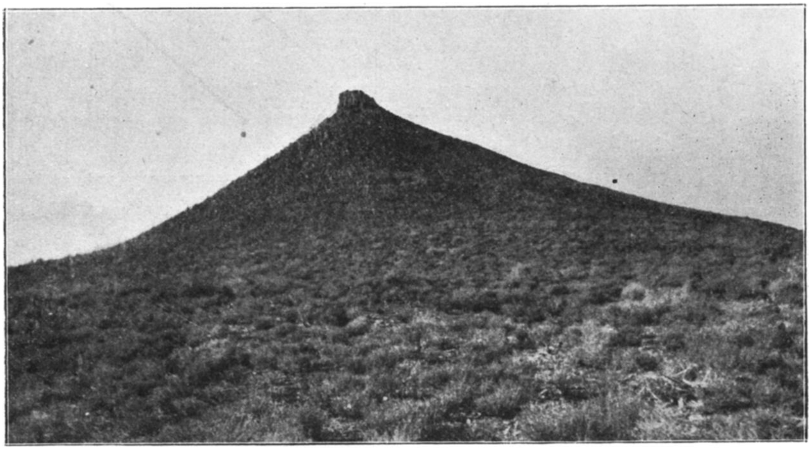


FIG. 10.—Sugarloaf mesa, on the edge of the Hurricane escarpment, west of Gould's ranch. A small basaltic cap protects a few hundred feet of Verkin shales, which recent erosion has elsewhere stripped off to the level of the Aubrey platform seen in the foreground.

SUMMARY.

The post-Eocene history of the Toquerville district has been characterized by two periods of upheaval, separated and followed by periods of relative quiet. In the first period, which was doubtless of great duration, with an unknown amount of erosion, occurred the original folding, the eruption of andesite upon a surface, but slightly, if at all, dissected, the reversal of the direction of deformation, and the earlier faulting. In the Kanarra section the fault followed the greatest of the folds, while in the portion south of Toquerville it traversed nearly horizontal plateau strata. These disturbances introduced the inter-fault cycle of erosion—a long period of comparative quiet, during which the outcrop-cliffs on the two sides of the fault receded northward at different rates, and the whole country was reduced to a degree of relief far less than the present. The southern region approached peneplaination, while toward the north the surface rose into graded mountainous hills separated by broad valleys. The close of this period was heralded by aggradation in the main valleys, and by extensive lava flows. In the second period of upheaval came the uplift of the Plateau province, marked by a displacement along the Hurricane and Grand Wash faults. The last period, or Grand Canyon cycle, has seen the cutting of numerous deep canyons and the stripping of large areas of soft strata; but its main work as a cycle of erosion is as yet only begun.

ELLSWORTH HUNTINGTON.
JAMES WALTER GOLDTHWAIT.